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INVESTIGATION OF LOW-DENSITY SYMMETRY ENERGY VIA NUCLEON AND FRAGMENT OBSERVABLES

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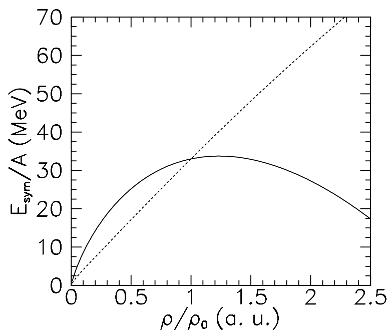
With stochastic transport simulations we study in detail central and peripheral collisions at Fermi energies and suggest new observables, sensitive to the symmetry energy below normal density.

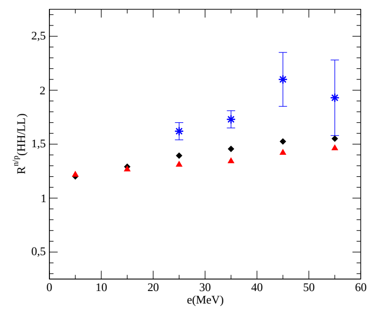
Keywords: symmetry energy, isospin transport coefficients, neck fragmentation

There has been much interest in recent years in the determination of the nuclear symmetry energy as a function of density, which is important for the structure of exotic nuclei as well as for astrophysical processes. Heavy ion collisions (HIC) present an attractive way to constrain the the existing models for this poorly-determined isovector equation-of-state (iso-EOS),[1] which can be investigated both at densities above and below normal density with relativistic energies and in the Fermi energy domain, respectively. However, observables, which are both sensitive to the iso-EOS and testable experimentally, still have to be identified clearly.[2,3]

In this report we discuss dissipative collisions at Fermi energies. Isospin dynamics at low and intermediate energies and its relation to the symmetry energy has, in fact, attracted much attention in recent years in experiment as well as in theory.[4–7] Here we focus our attention on pre-equilibrium emission in central collisions and on the charge equilibration dynamics in peripheral collisions, where we expect to see



(a)



(b)

Fig. 1. (a) Density dependence of the symmetry energies used in the simulations presented here: asy-soft (solid) and asy-stiff (dashed).
(b)Double ratio of emitted neutron over proton yield in central ^{124}Sn+^{124}Sn (HH) over ^{112}Sn+^{112}Sn (LL) collisions at 50 $AMeV$ with asy-stiff (red triangles) and asy-soft (black diamonds) EOS as a function of nucleon kinetic energy. Data of Famiano et al.,[13] are given as (blue) stars.

symmetry energy effects. The interesting feature at Fermi energies is the onset of collective flows due to compression and expansion of the interacting nuclear matter. The isospin transport takes place in regions with density and asymmetry variations, and thus we expect to have contributions to the isospin current from charge and mass drift mechanisms.

We perform *ab initio* collision simulations using the microscopic Stochastic Mean Field (SMF) model. It is based on mean field transport theory with correlations from hard nucleon-nucleon collisions and with stochastic fluctuations acting on the mean phase-space trajectory.[8,9] Stochasticity is essential in order to allow the growth of dynamical instabilities with fragment production, and to obtain physical widths of distributions of observables. A detailed description of the procedure is given in ref.[2] and in refs. therein.

We have used a generalized form of effective interaction with momentum dependent terms in the isoscalar and the isovector channel,[10] which is an asymmetric extension of the Gale-Bertsch-DasGupta (GBD) force.[11] The parameters are chosen to give a soft equation of state for *symmetric* nuclear matter (compressibility modulus 215 MeV, isoscalar effective mass $m^*/m = 0.67$), which is held fixed. Here we want to test the sensitivity of isospin transport observables to two essentially different behaviors of the symmetry energy around saturation: *asy-soft* and *asy-stiff*.[2] In Fig.1a we show the density dependence for these two typical choices. The *isoscalar* momentum dependence has been found to be important for the general dynamics, in particular the particle flow, of HIC.[12] To discuss its influence also on isospin dynamics we consider here interactions with (MD) and without (MI) momentum dependence. The *isovector* momentum dependence changes the proton/neutron ef-

fective masses and is still very controversial.[1,2] It is most effective at higher energies, but it effects are also evident in the Fermi energy range in pre-equilibrium emission.[10]

Isospin transport is closely connected to the value and the slope of the symmetry energy at a given density. In fact, the p/n currents can be expressed as

$$\mathbf{j}_{p/n} = D^{\rho}_{p/n} \nabla\rho - D^{\beta}_{p/n} \nabla\beta$$

with $D^{\rho}_{p/n}$ the mass (drift), and $D^{\beta}_{p/n}$ the isospin transport (diffusion) coefficients (asymmetry $\beta = (N-Z)/A$), which are directly given by the n,p chemical potentials.[4] Of special interest here is the difference of neutrons and protons currents (iso-vector current) for which the transport coefficients are proportional to[4]

$$D^{\rho}_{n} - D^{\rho}_{p} \propto 4\beta \frac{\partial E_{sym}}{\partial \rho}\,,$$
$$D^{\beta}_{n} - D^{\beta}_{p} \propto 4\rho E_{sym}\,.$$

Referring back to Fig. 1a we see that isospin drift and diffusion behave very differently for the two iso-EOS's.

Preequilibrium nucleons and light clusters are emitted in the approach and overlap stages of a HIC. The ratio of neutron to proton yields, (resp. of isobaric light cluster yields) carries information on the isospin forces. To reduce effects of secondary emission double ratios between different reactions have been investigated for nucleons[13,14] and IMF's.[15] We show a result from our calulations for nucleons in the "gas" phase (defined by a density cut of $\rho/\rho_0 < 1/6$) in Fig. 1b. It is seen that the asy-soft EOS is more effective, since the symmetry energy is higher below normal density (see Fig. 1a).

However, the iso-EOS effect is not very large, and both results are considerably below the data,[13] which, unlike in our calculations, are taken with a transverse angular cut. Already the results for the single n/p yield ratios deviate strongly from the experiment, which are very much higher for low energy nucleons. Our result is also in contrast to other calculations,[13,14] which show a stronger iso-EOS effect. Obviously, both the experimental data and the calculations have to be understood better. We also mention, that the effect of different neutron/proton effective masses, i.e. of an isovector momentum dependence, is of considerable influence already in this energy range,[10] but does not resolve the discrepancies noted above. The calculations shown in Fig. 1b are taken for the choice $m^*_n > m^*_p$.

In peripheral collisions of nuclei with different asymmetries isospin is equilibrated through the neck, mainly due to isospin gradients (diffusion). The amount of isospin transport has been measured with the so-called imbalance (or isospin transport) ratio,[16] which is defined as

$$R^{\beta}_{P,T} = 2\frac{\beta^M - \beta^{eq}}{\beta^{HH} - \beta^{LL}}\,,$$

with $\beta^{eq} = (\beta^{HH} + \beta^{LL})/2$. Instead of the asymmetry $\beta = (N-Z)/A$, one has also considered other isospin sensitive quantities, such as isoscaling coefficients.[19]

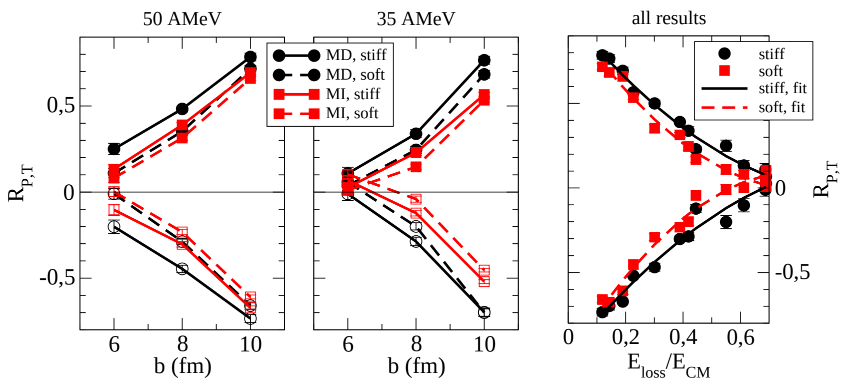


Fig. 2. (a) Imbalance ratios for $Sn+Sn$ collisions for incident energies of 50 (left) and 35 $AMeV$ (right) as a function of the impact parameter for asy-stiff and asy-soft EOS (signatures see legend box), projectile rapidity (upper curves), target rapidity (lower curves).
(b)Imbalance ratio for all results in part (a) but as a function of relative energy loss for asy-stiff (black dots) and asy-soft (red squares) EOS. Quadratic fit to all points for the asy-stiff (solid), resp. asy-soft (dashed) EOS.

The indices HH and LL refer to the symmetric reaction between the heavy (n-rich,^{124}Sn) and the light (n-poor,^{112}Sn) systems, while M refers to the mixed reaction, and P, T denote the PLF and TLF rapidity regions. Clearly, this ratio is ± 1 for complete transparency, resp. complete rebound, while it is zero for complete equilibration. Indeed, it can be shown, that the imbalance ratio depends on the magnitude of the symmetry energy and the interaction time. It is a very sensitive observable, magnifying small differences in asymmetry.

Results for our system as a function of impact parameter for different beam energies are shown in Fig. 2a. It is seen that the equilibration is larger (R smaller) for an asy-soft EOS (as expected from above), and for MI interactions and lower energy. The last two observation are fairly obvious, since they are due to longer interaction times (since the collision is also faster for the repulsive MD forces). It is therefore profitable to consider the imbalance ratio as a function of the interaction time, or an observable which is closely correlated to it. Such an observable is the total kinetic energy loss, which has been extensively investigated in dissipative collisions.[17] We thus show the imbalance ratios as a function of the relative energy loss per particle in Fig. 2b. Here all results for MD/MI interactions and 35/50 $AMeV$ are collected and - to guide the eye - are fitted by a quadratic curve for the asy-stiff and asy-soft EOS's separately. It is now seen that the results presented in this way are *only* sensitive to the iso-EOS, albeit with some scatter. Such a representation should be useful to obtain a unifying picture of different experiments as well as calculations.

In peripheral collisions a third intermediate mass particle (IMF) can appear, which originates in the rupture of the neck (ternary event, neck fragmentation).[18] This has been studied also experimentally in asymmetric collisions, in particular

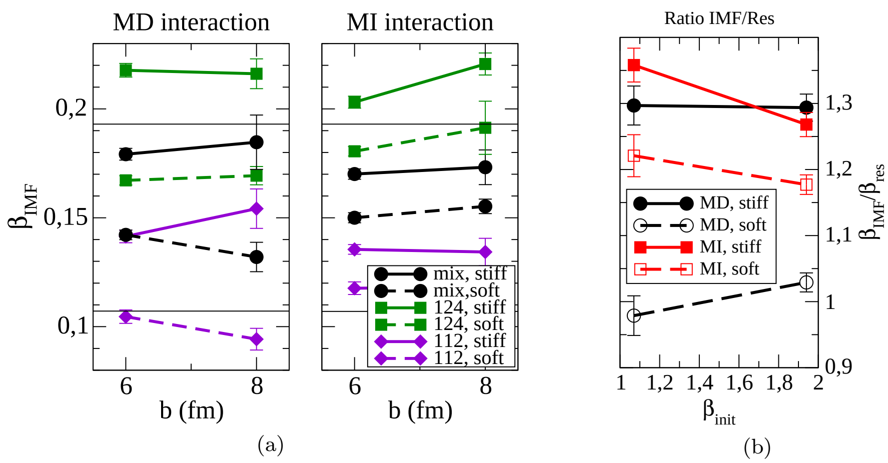


Fig. 3. (a) Asymmetries of IMF's in ternary Sn+Sn reactions at 50 AMeV as a function of impact parameter for MD (left panel) and MI (right panel) interactions for mixed and symmetric $Sn+Sn$ collisions for asy-stiff and asy-soft EOS's (see legend box). Horizontal thin lines: asymmeties of ^{124}Sn and ^{112}Sn, respectively.
(b) Ratios of asymmetries of IMF to residues for symmetric $Sn + Sn$ reactions at $50 AMeV$ as a function of the initial asymmetry for $b = 6fm$ for MD and MI interactions (see legend box).

with respect to velocity correlations between the residues and the IMF and to the alignment of the IMF.[20] In this report the isospin content of the IMF is of special interest, since it is mainly influenced by isospin transport due to density gradients, i.e. isopin drift or migration, which according to the above is governed by the slope of the symmetry energy below normal density. The asymmetry of the IMF in ternary reactions in our systems is shown in Fig. 3a both for the symmetric and the mixed $Sn + Sn$ collisions.

The asymmetry of the IMF is larger, i.e. the IMF is more n-rich, for the stiff relative to the soft iso-EOS, since the former exhibits a larger isospin migration due to the larger slope of the symmetry energy below saturation. This is clearly the case for the symmetric reactions, but it is also true for the mixed reactions, where there is a competition with isospin diffusion, which depends on the value of the symmetry energy and it is larger for the soft iso-EOS. Our result then shows that the isospin migration is the dominating effect for the asymmetry of the neck fragments. It is also seen that the difference between stiff and soft iso-EOS is particularly large for MD interactions, which can be traced back to the fact that the IMF's originate from more compact configurations.

The sensitivity to the IMF asymmetry can be enhanced by taking the ratio relative to the asymmetry of the residue, which is shown (only for the more transparent symmetric reactions) in Fig. 3b, as a function of the initial asymmetry. The large, almost 30% effect for the more realistic MD interaction is noteworthy. Thus this quantitiy, which should also not be very sensitive to secondary evaporation, may constitute a promising observable to gain more information on the symmetry en-

ergy. One may even consider double ratios of this quantity in reactions of HH over LL Sn isotopes.

We have shown that there exist several observables which should be able to yield information on the ill-determined low-density symmetry energy. Here we have investigated ratios of pre-equilibrium particles in central collisions and isospin transport between the residues and to the neck in peripheral collisions. We suggest to study the imbalance ratio not only as a function of centrality, but also depending on the energy loss in the reaction. We have also identified the asymmetry of an IMF from the neck as a promising observable. Unfortunately, however, both the agreement of theoretical calculations with each other as well as the comparison with experimental data are still far from satisfactory, such that the question of the isovector EOS has to be considered still open. Generally, the investigations into the low density iso-EOS favor an asy-stiff EOS from the isospin diffusion and the neck fragmentation data, and rather an asy-soft behavior from the pre-equilibrium studies. Further intensive work, perhaps also with data from more asymmetric radioactive beams, is highly desirable.

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